Scramjet Fuel Feed System Modelling for Flight and Ground Expulsion Trials

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Abstract

ISRO's scramjet characterization flight uses gaseous hydrogen (GH_2), as fuel and atmospheric air as oxidizer. Fuel Feed System (FFS) is one of the major sub-systems in the scramjet characterization flight which ensures injection of required quantity of fuel towards two scramjet engines. FFS consists of two GH_2 bottles, pressure regulator and orifices, connected using feedlines. Hydrogen is supplied to the engine through choked orifices, so that any fluctuation in the engine chamber pressure may not affect the flow rates. A detailed transient flow and thermal model is developed to determine the pressure at orifice inlet and flow rate during ground flow qualification test. Subsequently, the model is used to determine the evolution of gas bottle pressure, flow rate and regulated flow duration through FFS for ground GH_2 expulsion test as well as for scramjet characterization flight. The model is able to capture the flow physics and pressure evolution obtained during the ground expulsion trials and flight.

Keywords Fuel Feed System, Orifice, GH_2, Choked Flow, Gas Bottle

Nomenclature

β	Coefficient of volume expansion (K^{-1})
γ	Specific heat ratio
μ	Absolute viscocity (Pa.s)
ρ	Density (kg/m^3)
A	Area (m^2)
C_d	Coefficient of discharge
C_p	Specific heat capacity (J/kg.K)
D	Diameter (m)
g	Acceleration due to gravity (m/s^2)

h_c Heat transfer coefficient ($W/m^2.K$)

H Enthalpy (J/kg)

k Thermal conductivity (W/m.K)

L Length (m)

m Mass (kg)

$\dot{m}$ Mass flow rate (kg/s)

Nu Nusselt Number

P Pressure (bar)

Pr Prandtl Number

Q Heat rate (W)

r Roughness factor

R Specific gas constant (J/kg.K)

Ra Rayleigh Number

Re Reynolds Number

t Time (s)

T Temperature (K)

U Energy (J)

v Velocity (m/s)

V volume (m^3)

z Compressibility factor

Subscripts

c Cross-section

d Downstream

f Fluids

g Gas

s Surface

u Upstream

w Wall

1. Introduction

Scramjet engine was successfully demonstrated by ISRO during Scramjet characterisation flight. Major components of the flight are fuel feed system (FFS), dual mode ramjet engine (DMRJ) and booster. FFS plays a significant role in supplying fuel to

the engine as per the requirement. GH_2 is used as fuel for the twin scramjet whereas atmospheric air is the oxidiser. GH_2 is stored in two carbon epoxy wound Ti-6Al-4V gas bottles. Two gas bottles and pressure regulator module are positioned in fuel storage system (FFS), which is located in between nose cone and sustainer motor of the vehicle. GH_2 is stored in two bottles each of 35.5 litre capacity at 275 bar pressure and at 308 K temperature. GH_2 flow is regulated within 51-52.55 bar using GH_2 regulator module and is supplied to the engine via orifices to ensure the required fuel flow rate is achieved. For this purpose, a manifold containing multiple orifices is placed upstream to the inlet of engine thrust chamber.

During the blow down of gas bottles, the gas cools as a result of its expansion. This reduction in gas temperature results in increasing the flow rate due to increase in density. In order to maintain the mass flow rate with in the required range during engine operation, multiple orifices are required with sequential closing of each orifice as flow rate reaches its maximum limit. In this regard, a transient flow and thermal model is developed to simulate the expansion inside the gas bottle and its flow up to the orifice. The model is used to determine the flow characteristics during ground tests as well as for flight conditions.

2. Ground Test and Flight Configuration

Ground qualification test for FFS is carried out to characterize the feedline pressure drop and fluid flow rate in the system. Subsequently, gas bottle expulsion tests are carried out to determine the transient temperature profile of fluid through FFS and resulting variation in flow rate, so as to determine the orifice size. Finally, FFS is integrated to the engine for scramjet characterisation flight.

2.1 FFS flow qualification test

Ground qualification test for FFS flow is carried out using gaseous nitrogen (GN_2) at 300K to determine the pressure drop in the feedline. Pressure regulator supplies GN_2 at a pressure nearly 50bar. Since GN_2 source tank volume is sufficiently large, there is no cooling of GN_2 due to thermodynamic expansion, resulting in constant supply of 300K GN_2 at regulator inlet. Fig. 1 shows the feedline configuration for the flow qualification test. Feedline from pressure regulator outlet to orifice module is 5m in length and made of aluminium alloy. Required GN_2 flow rate is achieved using orifices. Mass flow meter, placed downstream of pressure regulator, is used to measure mass flow rate through FFS. Several tests for different pressures at outlet of pressure regulator are carried out and the results are compared with simulation results.

2.2 Gas Bottle expulsion test

Subsequent to flow qualification test, expulsion test is carried out to study the thermodynamic impact of GH_2 expulsion from the two gas bottles. The gas bottles are made of titanium alloy and are insulated with carbon epoxy. Figure 2 shows the schematic of FFS used for the gas bottle expulsion test.

It can be seen from Fig. 2 that each gas bottle is joined with pressure regulator inlet. The feedline configuration downstream to pressure regulator is the same as that used for qualification test. Regulated pressure varies from 51bar to 52.5bar for regulator inlet pressure range of 267bar to 73.3bar. Two orifices in parallel configuration are used to account the variation in flow rate due to gas thermodynamics. The expulsion tests provided an insight on the duration of regulated flow through FFS. Flow rate and pressure predictions are made prior to GH_2 expulsion test and are compared with test results.

2.3 Scramjet characterisation flight

Subsequent to GH_2 expulsion test in ground, scramjet engine is demonstrated in scramjet characterisation flight. The FFS configuration for flight is similar as GH_2 expulsion test configuration, shown in Fig. 2, with differences in feed line length and surrounding thermal conditions over FFS feedlines. In flight configuration, FFS feedlines are covered with cylindrical shell which results only in radiative heat transfer from the shell over the feedlines. Gas bottle pressure, pressure at orifice module inlet and duration of regulated flow are determined for flight configuration.

3. Mathematical formulation and solution methodology

A transient analytical model is developed for scramjet flight and test conditions, taking into account the corresponding gas bottle configuration and feedline system geometry. Flow and thermal model for gas bottle and flow lines are described in Fig. 3. Flow in a pipe is modelled as a series of discrete fluid nodes connected via flow lines. Model also takes into account the heat transfer from the wall to gas inside the bottle as well as in the flow lines by forced convection. A transient conduction analysis is carried out at the wall and insulation layers using temperature dependent properties of carbon epoxy insulation of gas bottle.

Mass and energy conservation equations are solved at the fluid nodes in conjunction with the thermodynamic equation of real fluid while momentum conservation

equations are solved at the fluid to fluid node connectors. The formulations used in the model are as below.

3.1 Mass conservation

The net mass flow from the fluid node must equate to the rate of change of mass in the control volume as shown below.

$$\dot{m}_u - \dot{m}_d = \frac{dm}{dt} \tag{1}$$

3.2 Energy conservation

The energy conservation equation is expressed on the basis of the first law of thermodynamics. The energy conservation equation based on enthalpy can be written as below:

$$\frac{dU}{dt} = (H_u.\dot{m}_u - H_d.\dot{m}_d) + Q \tag{2}$$

Where,

$$Q = h_c.A.(T_s - T_f) \tag{3}$$

The rate of increase of internal energy in the control volume is equal to the rate of energy transport into the control volume minus the rate of energy transport from the control volume.

3.3 Momentum conservation

The governing equation for flow connectors is simply a complex form of Newton's second law. The momentum conservation equation for a fluid connector can be written as below:

$$\frac{d\dot{m}}{dt} = \frac{A}{L}.\left[(P_u - P_d) - f.\left(\frac{\dot{m}^2}{2.\rho.A_c^2}\right)\right] \tag{4}$$

Frictional factor 'f' is calculated using 'Churchill formulation' [1] for turbulent flow as shown below:

$$f = 8.\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(a+b)^{3/2}}\right]^{1/12} \tag{5}$$

Where:

$$a = \left[-2.457.\ln\left(\left(\frac{7}{Re}\right)^{0.9} + \frac{0.27.r}{D}\right)\right]^{16} \quad (6)$$

$$b = \left(\frac{37530}{Re}\right)^{16} \quad (7)$$

3.4 Resident mass

The resident mass in fluid node volume can be expressed from the equation of state for a real fluid.

$$m = \frac{P.V}{z.R.T} \quad (8)$$

3.5 Pressure drop

Pressure drop in the flow line is calculated from 'Darcy-Weisbach formulation' described as follows.

$$\Delta P = \frac{f.L.\rho.v^2}{2.D} \quad (9)$$

3.6 Heat transfer in flow line

Each fluid node is connected with a surface node and surface node is connected with boundary node for energy transfer as shown in Fig. 2. Convective heat transfer coefficient (h_c) is calculated by 'Dittus- Boelter equation' [2] for turbulent flow as shown below:

$$h_c = \frac{Nu.k}{D} \quad (10)$$

$$Nu = 0.023.(Re)^{0.8}.(\mathrm{Pr})^{0.4} \quad (11)$$

3.7 Heat transfer in gas bottle

Heat transfer inside the gas bottle during expulsion is calculated by 'WoodField' [3] formulation as described below.

$$h_c = \frac{Nu.k}{D} \quad (12)$$

Where:

$$Nu = 0.104.(Ra)^{0.352} \tag{13}$$

$$Ra = \frac{g.\beta.(T_w - T_g).C_p.\rho^2.D^3}{\mu.k} \tag{14}$$

3.8 Heat transfer from ambient

Heat transfer from ambient to flow system is in the form of convection as well as radiation. Convective heat transfer coefficient is calculated by 'Churchill formulation' [2] as shown below.

$$Nu = 0.3 + \frac{0.62\,.Re^{0.5}.Pr^{0.33}}{\left(1+\left(\frac{0.4}{Pr}\right)^{2/3}\right)^{0.25}}\left[1+\left(\frac{Re}{28200}\right)^{5/8}\right]^{4/5} \tag{15}$$

3.9 Flow through orifice

The flow through the orifice in chocked condition [4] is calculated by equation as described below:

$$\dot{m} = C_d.A\left[\gamma.P.\rho\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{0.5} \tag{16}$$

4. Analysis results and discussions

Detailed thermo and fluid dynamic model of FFS is used to predict the flow rate and orifice module inlet pressure prior to flow qualification test, gas bottle expulsion test and scramjet characterization flight. Duration of regulated gas flow through FFS is also predicted for expulsion test and flight. In this section, the analysis results are compared with measurements from the experiments.

4.1 Analysis for flow qualification test

Flow qualification tests were carried out taking the line configuration as shown in Fig.1. The analysis considers the flow from pressure regulator outlet to orifice manifold consisting of two orifices. Different tests were carried out with different outlet pressures of pressure regulator using gaseous nitrogen as flow medium. Orifice area of smaller orifice is determined to be 10% of that of bigger orifice. The simulated flow rates and pressure

drop through FFS matches well with the test measured data. Thus, the mathematical model is well validated with results from flow qualification test.

4.2 Analysis for gas bottle expulsion test

Transient analyses were carried out for GH_2 bottle expulsion tests and simulated parameters are compared with test data. The model considers flow and thermal aspects such as thermodynamics inside gas bottle, heat transfer from feedline surface to fuel, pressure drop inside feedline and flow through choked orifices. At the start of expulsion test, GH_2 temperature and pressure inside gas bottle was 288K and 276.5bar respectively. GH_2 flow is controlled by two orifices, as shown in Fig.2. The smaller orifice size is determined to be 8% of bigger orifice size and is closed at t=3.0s to maintain the required flow rate.

The comparison of simulated bottle pressure with the measured test data is shown in Fig. 4. It can be seen from Fig. 4 that simulated bottle pressure is well comparable with the measurement data. Simulated orifice inlet GH_2 pressure and temperature are compared with test data in Figs. 5 and 6, respectively. Gradual increase in orifice inlet pressure, seen in Fig. 5, is due to characteristics of pressure regulator. At t=3.0s, the smaller orifice is closed, which results in reduction in flow rate and pressure drop in feedline, causing pressure rise at orifice inlet, as seen in Fig. 5. It is also noted that upto t=5.28s, pressure regulator is regulating the GH_2 pressure. Subsequently, the regulator outlet pressure follows the same pattern as bottle pressure due to insufficient pressure at regulator upstream. The simulated regulated mode duration is 5.23s in comparison with measured duration of 5.28s. Reduction in orifice inlet temperature, seen in Fig. 6, is due to thermodynamic expansion of GH_2 in gas bottles, which is well captured by the model.

GH_2 flow rate through FFS, after normalizing with the flow rate at start of engine ignition, is shown in Fig. 7. It can be seen from Fig. 7 that GH_2 flow rate increases with time. This is due to reduction of GH_2 temperature at orifice inlet, as seen in Fig. 6. Subsequently, after the regulated mode, the pressure at inlet of pressure regulator is less than the pressure regulation range of 51bar to 52.55bar, resulting in blow down mode of GH_2 flow, causing orifice inlet pressure (Fig. 5) and flow rate through FFS (Fig. 7) to reduce gradually.

Thus, both the orifices, used for controlling GH_2 flow into scramjet engine, are successfully qualified during expulsion test. The present transient model is consistent with ground expulsion test data.

4.3 Analysis for scramjet characterisation flight

Subsequent to the model validation with flow qualification test and bottle expulsion tests, the analysis was carried out for scramjet characterisation flight. The initial GH_2 pressure inside gas bottle is 278.3bar. Flow is controlled by two orifices of same sizes as in GH_2 expulsion test. The smaller orifice is closed at 3.0 seconds after GH_2 expulsion.

Figure 8 shows the comparison of simulated bottle pressure with flight data and is well captured by the analytical model. Figure 9 shows orifice inlet pressure pattern during characterisation flight. The simulated value of regulated flow duration is 5.62s, as seen in Fig. 9, which is close to the observed value of 5.56s.

5. Conclusion

A detailed transient flow and thermal model is developed to determine flow rate and orifice size for realization in Scramjet characterization flight (ATV-02) after predicting FFS parameters for ground flow qualification test and ground bottle expulsion test. Ground flow qualification test is carried out with GN_2 to estimate the pressure drop across FFS feedline. Predicted orifice inlet pressure is in in good agreement with qualification test. Subsequent prediction for GH_2 flow rate, gas bottle pressure and duration of regulated flow through FFS during expulsion test showed good agreement with test data. The orifice sizes for FFS in Scramjet characterization flight are finalized from pre-flight model simulation. Successful scramjet flight proved the robustness of the present mathematical model.

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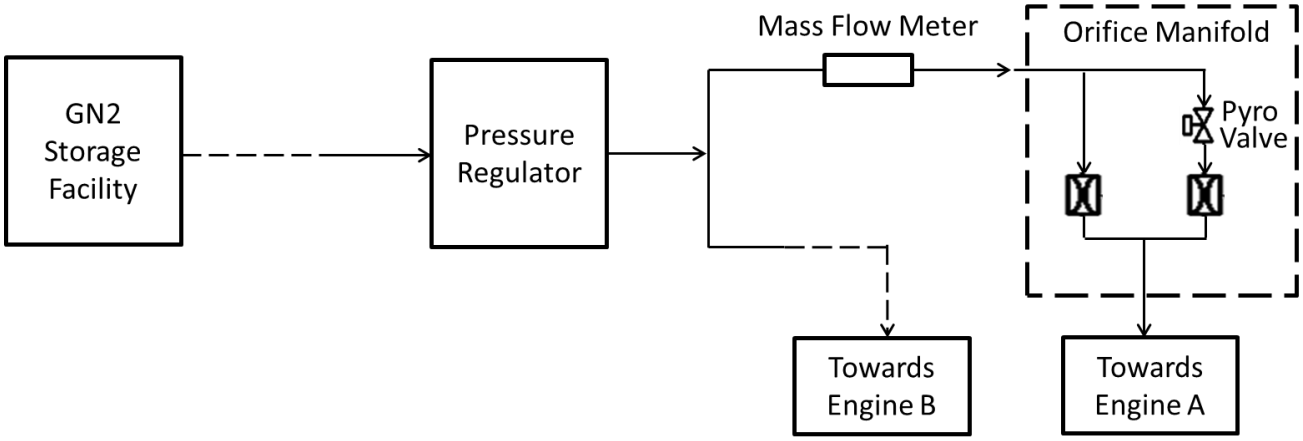

Fig. 1 Schematic of test setup for ground flow expulsion test

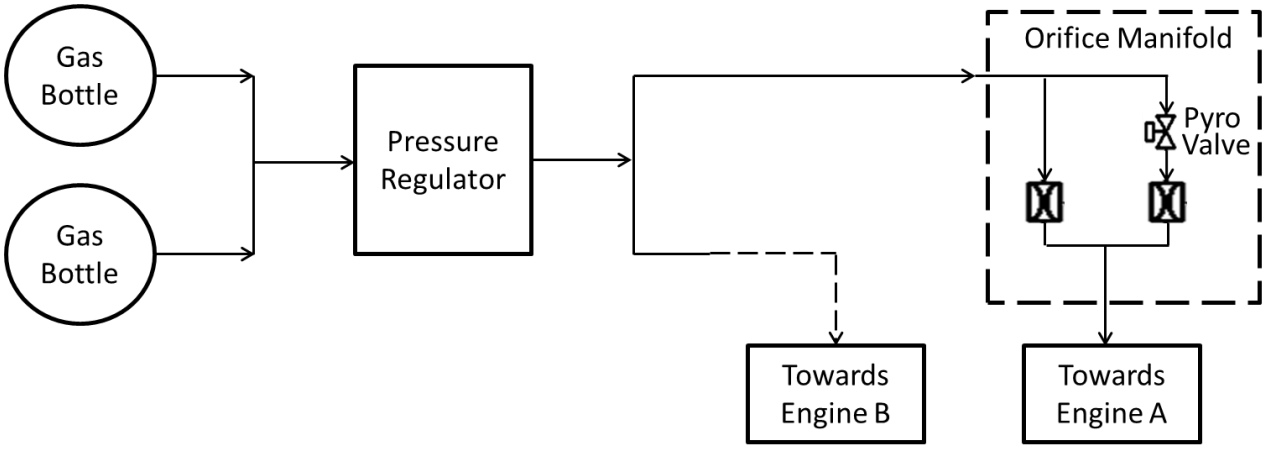

Fig. 2 Schematic of FFS configuration for expulsion test and characterisation flight

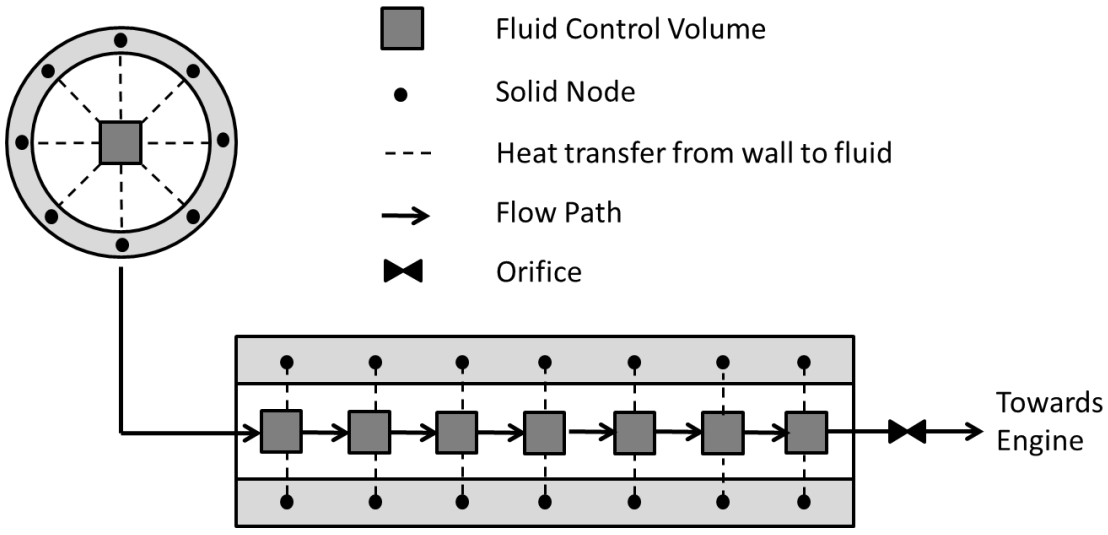

Fig.3. Flow and thermal model for gas bottle and flow lines

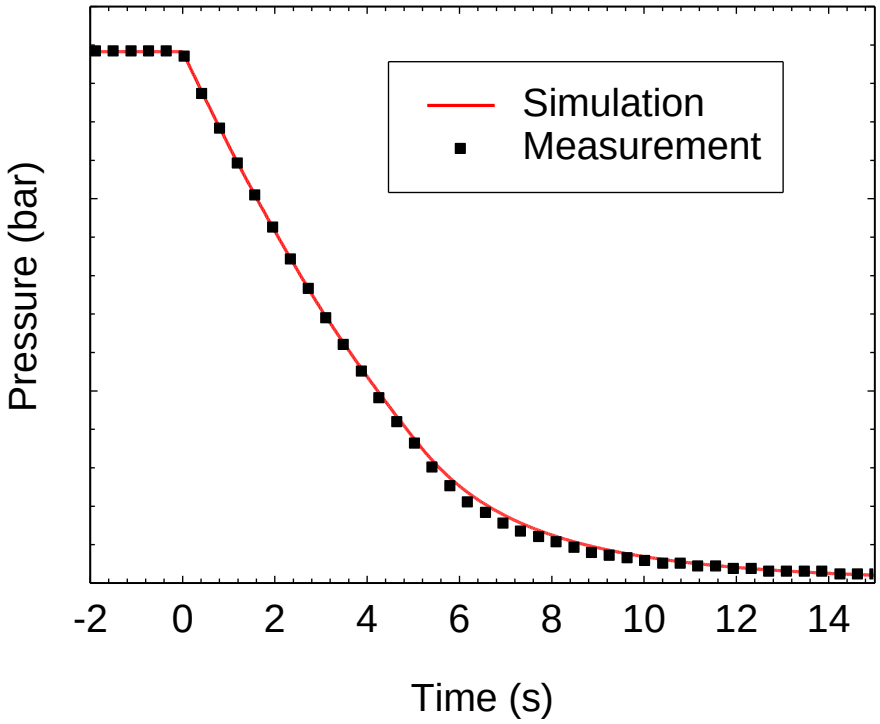

Fig.4. Gas bottle pressure during expulsion test : simulation vs measurement

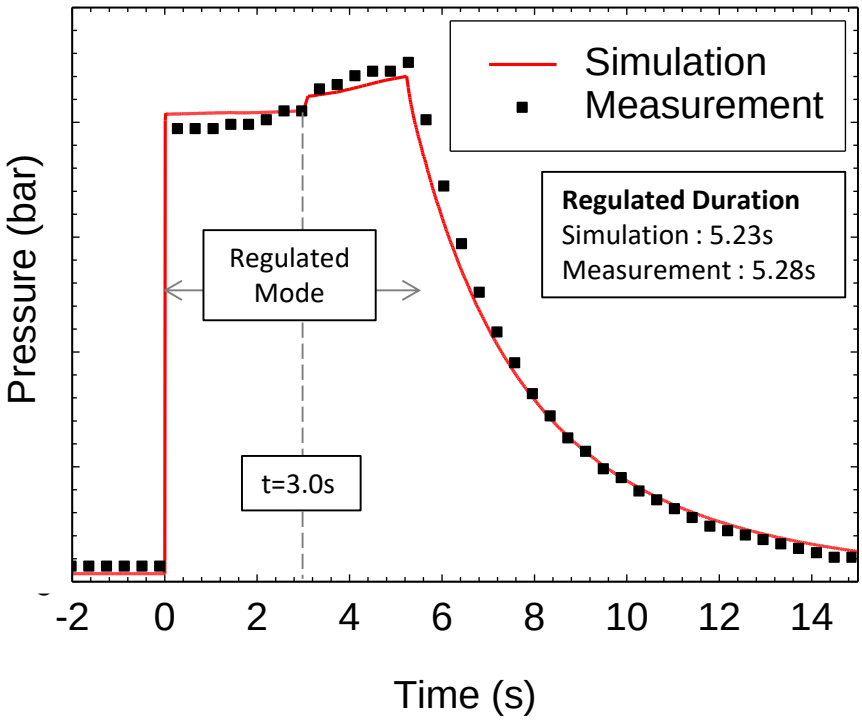

Fig. 5. Orifice inlet pressure during expulsion test : simulation vs measurement

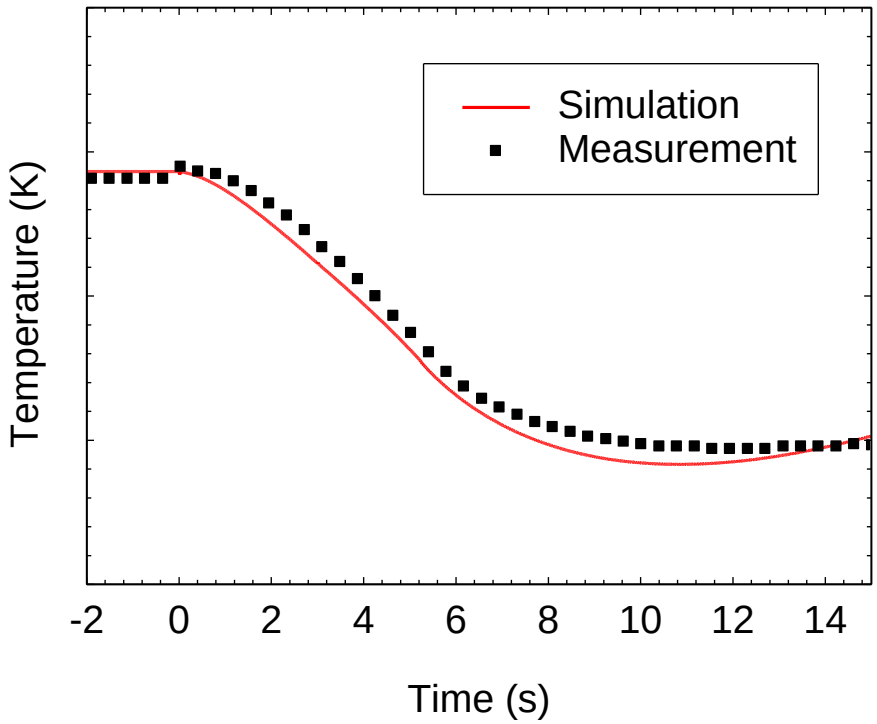

Fig. 6. Orifice inlet GH_2 temperature during expulsion test : simulation vs measurement

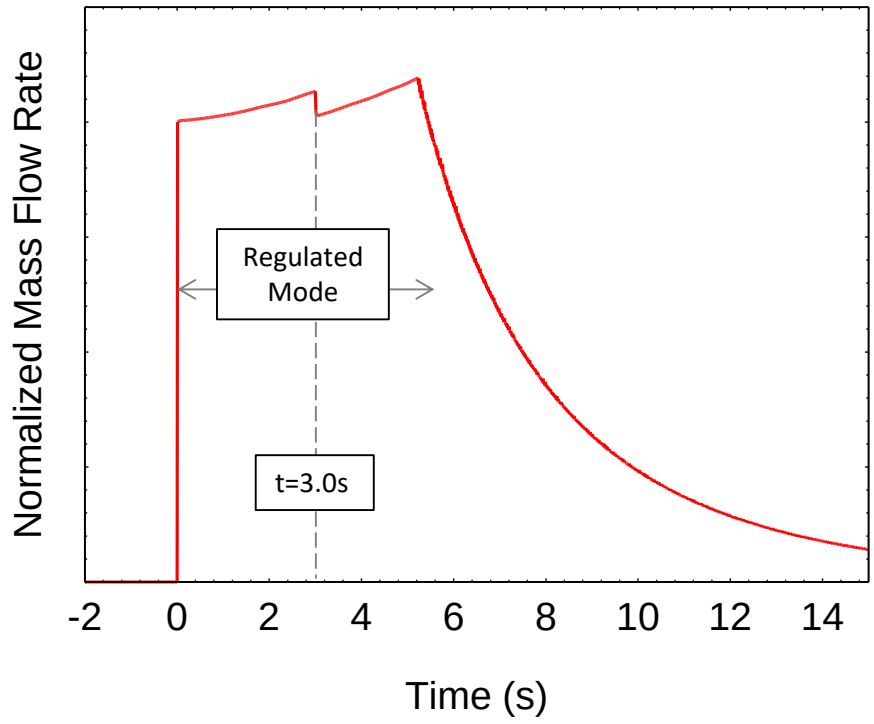

Fig. 7. Normalized GH_2 flow rate through FFS simulated for expulsion test

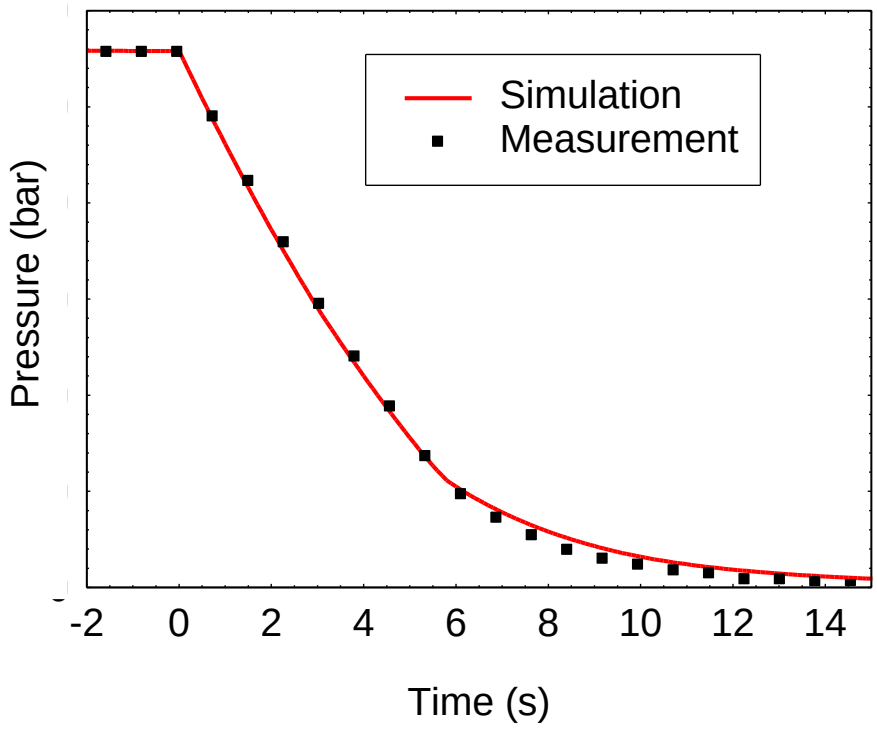

Fig. 8. Gas bottle pressure during scramjet characterization flight : simulation vs measurement

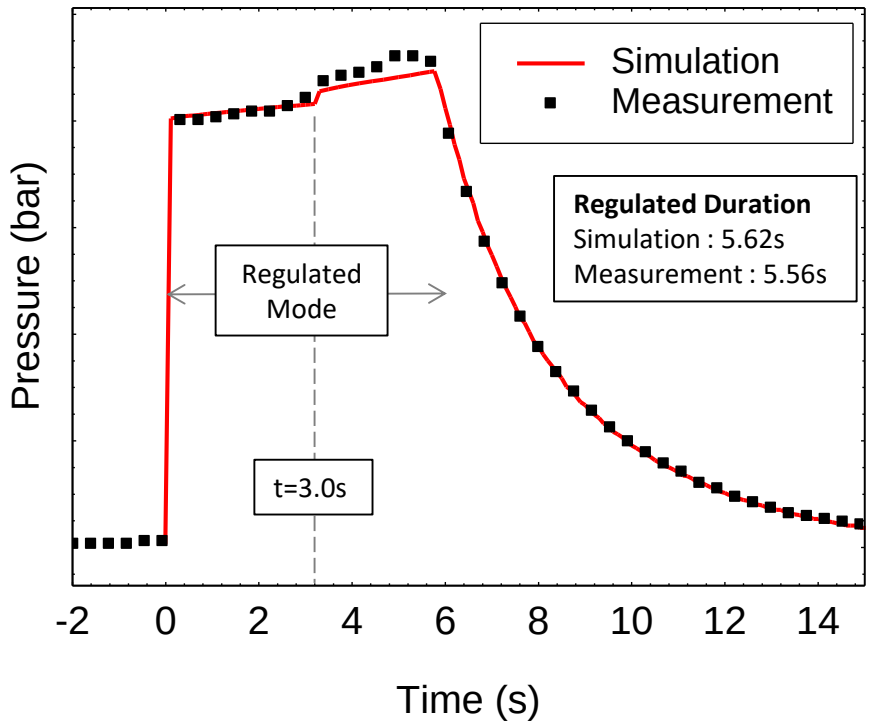

Fig. 9. Orifice inlet pressure during scramjet characterization flight : simulation vs measurement